

# Effect of Scaffold End Frame Carrying Strategies on Worker Stepping Response, Postural Stability, and Perceived Task Difficulty

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**Objective:** This study determined the most favorable strategy for carrying scaffold end frames while minimizing the risk of injuries from being struck by an object, falling, and overexertion. **Background:** Scaffold erectors are at risk of high exposure to the aforementioned hazards associated with the dynamic human-scaffolding interface and work environments. Identifying an optimal work strategy can help reduce risk of injuries to the worker. **Method:** Three carrying methods, four types of work surfaces, two weights of scaffold frames, and three directions of stepping movement were tested in a laboratory with 18 construction workers. **Results:** The effects of carrying method on postural instability and task difficulty rating were significant for handling the 22-kg end frame. Response time, postural instability, and perceived task difficulty rating were significantly reduced when the 9-kg end frame was used as compared with the 22-kg frame. **Conclusion:** The symmetric side-carrying method was the best option for handling 22-kg scaffold end frames. A 9-kg end frame (e.g., made of reinforced lightweight materials) has the potential to reduce injury risk among scaffold handlers during their scaffold erection and dismantling jobs. **Application:** Scaffold erectors may want to adopt the symmetric side-carrying method as the primary technique for handling the 22-kg scaffold end frame, which is currently the one most used in the industry.

## INTRODUCTION

Being struck by an object, falling, and overexertion represented 25%, 21%, and 21% of 32,746 cases, respectively, of injuries resulting in days away from work in 2001 for carpenters who performed scaffold-handling jobs (Bureau of Labor Statistics, 2004), and carrying an end frame represented two thirds of the time spent during a typical scaffold-handling (i.e., erection and dismantling) cycle (Hsiao & Stanevich, 1996a).

Scaffolding work methods, worker abilities, and work environments can interactively affect the occurrence of these injuries during end frame carrying tasks (Hsiao & Stanevich, 1996b). A comprehensive evaluation of the work methods being performed by construction carpenters in scaffolding work environments, involving the simultaneous assessment of workers' stepping response,

postural instability, and perceived task difficulty during scaffold end frame carrying tasks, may identify the best work strategy that can reduce overall worker risk for the aforementioned injuries during their scaffold end frame carrying jobs.

First, stepping response time reflects a worker's ability to execute a stepping action to respond to changing conditions. Work environments or work methods that result in an increased worker stepping response time could increase the risk of an undesirable consequence, such as being struck by a falling object. As determined by the laws of physics, a free-falling object would reach the ground in 1.1 s from a 6-m (two-floor) height or in 2.2 s from a 24-m height. In a pilot study by the authors, healthy adults were found to take 0.78 to 2.16 s to complete a step-forward movement on a firm surface after seeing a signal.

Additional workloads, such as carrying an end

frame and walking on nonrigid surfaces, may affect a person's stepping response ability and thus increase the risk of the worker being struck by an object, whether falling or moving horizontally. Failure to negotiate stepping actions adequately and in a timely fashion can also lead to a slip, trip, or fall. Although several studies have reported factors that affect the human response times of the arm and foot (Deupree & Simon, 1963; Hoffmann, 1991), little in the literature has addressed human stepping response ability, especially during load-carrying conditions.

Second, during scaffold erection and dismantling tasks, workers use various techniques to carry scaffold end frames on narrow and deformable surfaces (i.e., planks) aboveground. These conditions may adversely affect workers' postural stability and increase their risk of falling. Neurological input from the human sensory systems leads to the selection and execution of motor responses to control and recover balance functions, on a continuous basis (Viallet, Massion, Massarino, & Khalil, 1992); the inability of individuals to adapt to changing tasks or environmental factors has been reported to contribute to decreased postural stability and thus an increased risk of falls (Hanson, Redfern, & Mazumdar, 1999). Carrying an object, especially a heavy object, can adversely affect an individual's adaptation control and, thus, postural stability (Holbein & Redfern, 1997).

Prospective studies have identified relationships between postural sway and the risk of falling (Ferne, Gryfe, Holliday, & Llewellyn, 1982; Maki, Holliday, & Topper, 1994). Under ideal conditions of upright postural stability, a person would produce minimal sway, whereas poor postural stability would result in a significant increase of most sway parameters, such as sway area, sway velocity, and center-of-pressure displacement.

Third, scaffold workers' body strength capability is significantly affected by their work postures (Cutlip, Hsiao, Garcia, Becker, & Mayeux, 2000); certain techniques for carrying scaffold end frames can induce overexertion in some workers (Hsiao & Stanevich, 1996a). A welded, tubular scaffold end frame is typically 1.52 m wide by 2 m high and weighs about 22 kg. This borders the threshold of the recommended weight limit under ideal conditions as described in the revised National Institute for Occupational Safety and Health (NIOSH) lifting equation (Waters, Putz-Anderson, Garg, & Fine, 1993). The restricted and potentially unsta-

ble scaffolding workspace has made the handling task even more challenging. Psychophysical stress assessments have been widely used in the ergonomics research community to evaluate overexertion risk associated with load handling; an assessment of worker-perceived task difficulty for each scaffold-carrying method would provide insight to help identify the most favorable method to reduce the risk of overexertion.

This study evaluated the effect of scaffold end frame carrying techniques on worker performance (i.e., stepping response time, postural stability, and task difficulty) using various end frame weights, work surfaces, and stepping directions.

## METHODS

### Participants

Eighteen male construction workers were recruited to participate in the study. The mean values and standard deviations for the participants' age, height, and weight were  $33.9 \pm 11.6$  years,  $177.8 \pm 3.6$  cm, and  $92 \pm 13.1$  kg, respectively. All participants had at least 6 months of scaffolding work experience and passed a physical screening test. The study protocol was approved by the Institutional Review Board of NIOSH.

### Independent Variables

*Carrying methods for end frames.* The scaffold end frame tested was 198 cm high by 152 cm wide and had a 3.2-cm tube diameter (Figure 1). It represented the most popular end frame used in the residential and commercial construction sectors. Three of the most commonly used methods for carrying scaffold end frames were evaluated in this study: the symmetric front-carrying, symmetric side-carrying, and asymmetric side-carrying methods (Figure 1; Hsiao & Stanevich, 1996a). The symmetric and asymmetric methods were defined such that hand placement was either symmetric or asymmetric to the sagittal plane of the torso, respectively.

*Weights of end frames.* Two end frame weights were used in this study. The regular, industrial end frame weighed 22 kg. The lightweight, simulated end frame weighed 9 kg, was custom made with plastic tubes, and had the same geometry and dimensions as a regular frame.

*Working surfaces.* Four surfaces were tested in this study. An unmodified force plate, representative of solid ground, metal planks, or composite

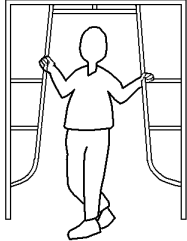
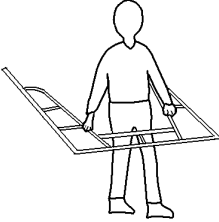
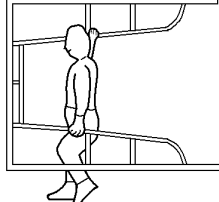
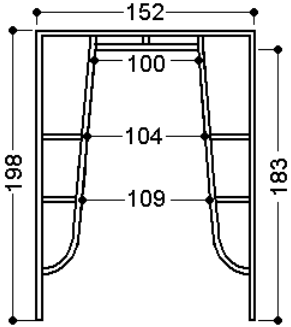
Method	Illustration	Description
<p>1</p> <p><b>Symmetric Front-Carrying</b></p>		<p>Walking with the wide axis of the frame parallel to the hips while gripping the frame on both sides at approximately chest height with palms facing away from the front of the body (thumb up). Defined as symmetric.</p>
<p>2</p> <p><b>Symmetric Side-Carrying</b></p>		<p>Walking with the wide axis of the frame perpendicular to the hips while gripping the frame on both sides at approximately hip height with palms facing down. Defined as symmetric.</p>
<p>3</p> <p><b>Asymmetric Side-Carrying</b></p>		<p>Walking with the right arm locked above the head in an upright position with the left arm placed to the side below waist level. Defined as asymmetric.</p>
<div style="display: flex; align-items: center;">  <div style="margin-left: 20px;"> <p>The tested industrial scaffold end frame was 198 cm high by 152 cm wide by 3.2 cm tube diameter, and weighted 22 kg. A simulated end frame, built with plastic tubes, had the same physical features and dimensions, and weighted 9 kg.</p> </div> </div> <p style="text-align: center;">All dimensions in cm (not to scale)</p>		

Figure 1. The three end frame carrying methods evaluated in this study.

planks, was used as a firm surface. Three urethane pads (5, 7.5, and 10 cm thick) with a density of approximately 50 kg/m<sup>3</sup> were each topped and glued with a layer of 1-cm plywood painted with slip-resistant paint. Each urethane pad was placed on a force plate to simulate three nonrigid surfaces having a range of deflection levels for a 5- × 30-cm × 2.5-m wood plank with a 90-kg worker standing

on the midpoint of the plank and holding a 22-kg scaffold end frame.

The deflections of 3, 4.5, and 6 cm were measured by placing a 112-kg weight on the urethane pads. These deflection values were approximately 50%, 75%, and 95%, respectively, of the maximum deflection level specified in the safety rules for scaffold planks in California Code of Regulations

title 8, section 1938, appendix C, plate C-17. The simulated non-rigid surfaces allowed the randomization of the deflection levels to be performed within a reasonable experimental time frame.

*Directions of stepping movement.* Three directions of stepping movement – forward, backward, and lateral – were investigated.

### Dependent Variables

*Stepping response time.* Stepping response time was the time required to perform a stepping task while carrying a scaffold end frame.

*Postural stability.* Four postural stability variables derived from center of pressure (CP) measurements were used to quantitatively describe postural sway and determine postural stability. The variables were the root mean square (RMS) of CP displacement in the medial-lateral direction (ML) and anterior-posterior direction (AP), mean velocity of CP displacement, and sway area.

These measurements have been widely used in geriatric studies (Hasan et al., 1996) and occupational safety research (Bhattacharya, Succop, Kincl, Lu, & Bagchee, 2002/2003; Simeonov, Hsiao, Dotson, & Ammons, 2003). The RMS of ML and AP represents a suitable measure for average body sway over a certain period of time and allows for an easy comparison to be made between the effects of different experimental conditions (Bles, Kapteyn, Brandt, & Arnold, 1980). Sway velocity is considered to be a valid measure of postural instability (Robbins, Waked, & Krouglicof, 1998); it correlates closely with the risk of falling (Ferne et al., 1982). In geriatric studies on decreased balance abilities or recurrent falls, sway area was found to be a predictive parameter (Perrin, Jeandel, Perrin, & Bene, 1997; Thapa, Gideon, Brockman, Fought, & Ray, 1996).

Two periods of data were used to assess these dependent variables. The data between the 3rd and 13th s (10-s interval) before a stepping action represent the sway during a semistatic end frame holding and carrying condition. The data between the 3rd and 6th s (3-s interval) after stepping execution represent the postural sway at the critical balance control phase. Data points taken between 0 and 3 s were excluded from the data analysis, as the “normal” sway signals would have been confounded with the “noise” resulting from stepping initiation and termination.

*Perceived task difficulty.* A 7-point Likert scale was used to assess the difficulty of scaffold-

carrying techniques in combination with the work surface, scaffold weight, and stepping direction conditions. The scores were 1 (*easy job*), 2 (*light work*), 3 (*normal task*), 4 (*somewhat difficult*), 5 (*difficult*), 6 (*very difficult*), and 7 (*physically fatiguing*). The scores reflected the ratios of the scaffold weights to a participant’s physical strength capacity while he assumed different work postures (carrying techniques) during different environment (work surface) and task (stepping directions) conditions.

### Apparatus

A Bertec Type 4060-08 force plate system (Bertec Corp., Columbus, OH) with four plates was used to measure the whole-body sway and whole-body response time by analyzing the vertical reaction and transverse forces against the feet. A computer monitor displaying four boxes (corresponding to the arrangement of the four force plates) and two warning lights (corresponding to rest and hold conditions) were placed at eye level 3.05 m in front of the participants. The top box indicated a forward step, the side box indicated a right-side step, the bottom box indicated a backward step, and the central box indicated the initial standing position. Participants were prepared for the step by the hold light turning off and one of the three “stepping action” boxes lighting up.

### Procedure

Participants attended two study phases. Phase 1 included a scaffold-handling demonstration and tests using the 22-kg end frame, and it lasted approximately 4 hr. Phase 2 was completed on a different day (approximately 3 to 5 weeks after Phase 1, to serve as an engineering-control evaluation) and included the tests using the 9-kg simulated end frame; it lasted approximately 3.5 hr. During Phase 1, the participants practiced the three carrying methods, with feedback from the researchers on hand postures, until they felt comfortable with performing each carrying method. The participants then performed 36 tasks (3 carrying methods × 3 directions × 4 surfaces). The 36 tasks were randomly assigned using a random number generator in the data collection program. Phase 2 repeated the same 36 tasks using the 9-kg end frame.

For all test-period tasks in both phases, participants wearing NIOSH-provided footwear held the end frame and stood quietly on the central force plate for 15 s while visually focusing on a

cue box 3.05 m in front of the central plate. Next, participants were signaled to step from the central force plate to the other plates, executing the movement indicated by the cue box. Participants stepped from the central force plate to the corresponding receiving force plate in response to the cued direction. Immediately after completing the stepping movement, the participants, holding the end frame and facing the cue box, stood quietly on the receiving force plate for 15 s. After each test, the participants gave a rating to the task condition in terms of perceived task difficulty for both pre- and post-stepping actions, using the 7-point Likert scale. The participants rested for 3 min between tests. After 18 tests, participants rested for 15 min before going on to the next trial.

The sample frequency of the force plates was set at 100 Hz. At the initial phase, the participants stood on the central force plate. The vertical force recorded was the participant's weight plus the weight of the end frame, and the CP of each trial was collected at this time. When the participants initiated a movement, the vertical ( $F_z$ ) and the transverse ( $F_x$  and  $F_y$ ) forces on the force plate changed significantly (Figure 2). The stepping response time was measured from a 20-N force change in any direction from the standstill position up to the point in time when the vertical force became zero. The CP data on the receiving force plate were also collected at the same time, using LabVIEW software (National Instruments Corp., Austin, TX).

## DATA ANALYSIS

Data analyses were performed by the general linear model procedure of the Statistical Analysis System (SAS). To evaluate the effect of experimental conditions on stepping response time, a univariate ANOVA was performed. Appropriate  $F$  tests were constructed for main effects and two-way interactions using the Effect  $\times$  Participant interaction as the denominator. The Bonferroni adjustment for the  $p$  values was used for multiple comparisons to determine the significance of differences among experimental conditions. The stepping response time measurements were transformed to their natural logarithm to achieve approximate normality of the statistical distribution.

For postural stability evaluation, a MANOVA was performed first to evaluate the overall effects of different experimental conditions on the four postural stability variables. Subsequent univariate ANOVAs were performed, and a subset of dependent variables that had both practical use and statistical significance were used to interpret the results. Appropriate  $F$  tests were constructed, and the Bonferroni adjustment for the  $p$  values was used for multiple comparisons.

For perceived task difficulty, the mean scores were compared among different experimental conditions. In addition, to account for intraparticipant correlations with repeated measurements on the same participant, the generalized estimating equations method (SAS GENMOD procedure) was used

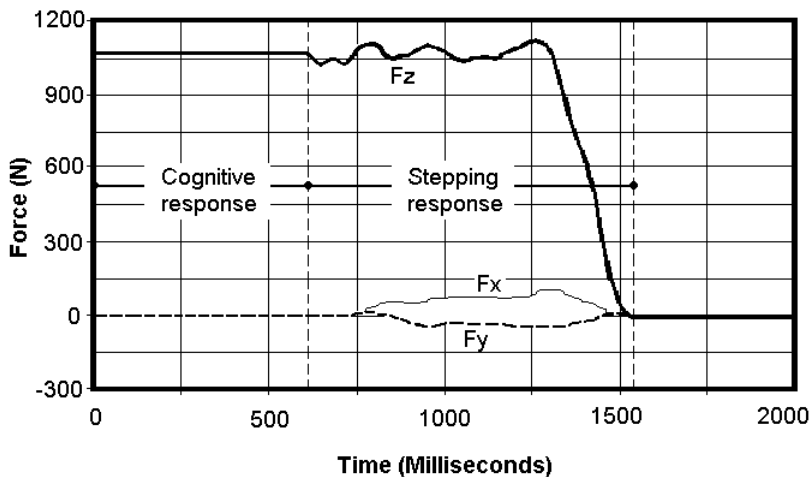


Figure 2. When the participants initiated a movement, the vertical ( $F_z$ ) and transverse ( $F_x$  and  $F_y$ ) forces on the force plate changed significantly. The stepping response time (between the dashed vertical lines) was measured from a 20-N force change in any direction from a quiet standing position up to the point in time when the vertical force became zero.

to evaluate the pre- and poststep perceived task difficulties as well as the increase in perceived task difficulty from the pre- to poststep phase. The 7-point Likert scale of perceived task difficulty was treated as an ordinal response variable, and a cumulative logic model was used to fit this ordinal data. For assessing the increase in perceived task difficulty, a binary outcome variable (increased vs. no increase) was generated, and the GENMOD procedure with alternating logistic regression approach was used to evaluate the experimental conditions associated with the increase in perceived task difficulty from the pre- to poststep phase.

## RESULTS

### Step Response Time

Significant effects were found for the Method  $\times$  Surface,  $F(6, 102) = 2.23, p = .047$ , and Weight  $\times$  Direction interactions,  $F(2, 34) = 4.94, p = .013$ , on step response time. The Method  $\times$  Surface combination that produced the fastest response time was symmetric front carrying on the firm surface (1.83 s or 0.61 natural logarithm s), and the slowest response time was for symmetric front carrying on the 10-cm thick surface (2.15 s or 0.77 natural logarithm s). For all carrying methods, all three nonrigid surfaces (except the 5-cm surface in asymmetric side carrying) showed significantly longer stepping response times than did the solid surface. Carrying the 22-kg scaffold frame demanded more response time than carrying a 9-kg frame when stepping sideways (1.91 vs. 1.8 s,  $p = .0045$ ) or backward (2.28 vs. 2.15 s,  $p = .024$ ). When stepping forward, there was no difference in stepping response time between the two weight conditions (2.0 vs. 1.99 s,  $p = .999$ ).

### Postural Stability

*Postural sway before a stepping action.* There was a significant two-way interaction of end frame weight with carrying methods ( $p < .05$ ) for all four postural stability measurements. With the 22-kg end frame, the symmetric front-carrying method resulted in the greatest postural sway among all three carrying methods, and this sway was significantly greater than that obtained with the symmetric side-carrying method for all four postural stability measurements ( $p < .05$ ). However, there was no significant difference among all three carrying methods when a 9-kg end frame was used (Figure 3).

A significant interaction of end frame weight with surface types was observed when measured by sway area,  $F(3, 51) = 3.25, p = .0291$ ; carrying a 22-kg frame resulted in greater sway area than carrying a 9-kg frame at various response rates among different surface levels, except for the solid surface. Surface level had a significant effect on the remaining three postural stability measurements (ML, AP, and sway velocity;  $p < .05$ ). Stepping on a 10-cm thick urethane pad had the highest instability, followed by 7.5-cm thick pad, 5-cm thick pad, and the solid surface. With the exception of the 5-cm thick pad surface condition measured in AP, all pairwise comparisons on sway measurements showed significant differences between the urethane pads and the solid surfaces ( $p < .05$ ).

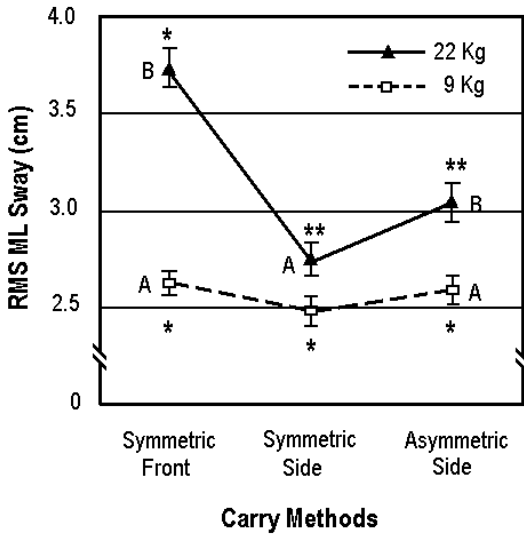
*Postural sway during the first 3 to 6 s after a stepping execution.* The analysis of RMS of CP displacement in the ML direction showed significant two-way interactions of end frame weight with carrying methods,  $F(2, 34) = 7.36, p = .0022$ , and surface type with direction of movement,  $F(6, 102) = 2.23, p = .0459$ . Symmetric front carrying was the least stable among all three carrying methods when the 22-kg end frame was used (2.83 cm), whereas no significant difference was observed when the 9-kg end frame was used.

The analysis of RMS of CP displacement in the AP direction showed significant effects of surface type,  $F(3, 51) = 7.68, p < .001$ , carrying method,  $F(2, 34) = 4.10, p = .025$ , and direction of movement,  $F(2, 34) = 24.12, p < .001$ . The solid surface resulted in less postural instability than did the 7.5-cm and 10-cm urethane pad surfaces. Symmetric side carrying was significantly more stable than asymmetric side carrying (1.89 vs. 2.17 cm,  $p < .05$ ). Stepping forward was significantly more stable than stepping laterally (1.64 vs. 2.17 cm,  $p < .05$ ) or backward (1.64 vs. 2.36 cm,  $p < .05$ ).

Analyses of sway velocity showed significant effects of surface type,  $F(3, 51) = 3.35, p = .0262$ , on sway velocity. The solid surface provided the most stable stepping surface when compared with various thicknesses of urethane pads; it was significantly more stable than the 10-cm thick urethane pad (7.31 vs. 8.69 cm/s,  $p < .05$ ).

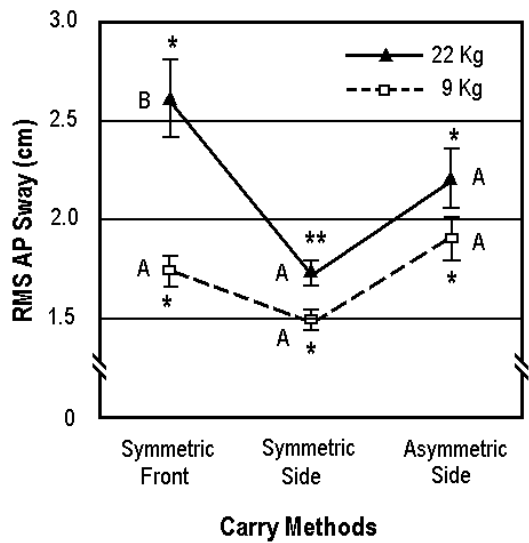
Analyses of sway area showed that the end frame weight,  $F(1, 17) = 4.52, p = .0484$ , surface type,  $F(3, 51) = 6.41, p = .0009$ , and direction of movement,  $F(2, 34) = 17.80, p < .0001$ ; all had significant effects on sway area. Carrying a 22-kg end frame resulted in a significantly larger sway

**End Frame Weight x Carry Method Interaction Effect on RMS ML Sway at Prestepping Stage**



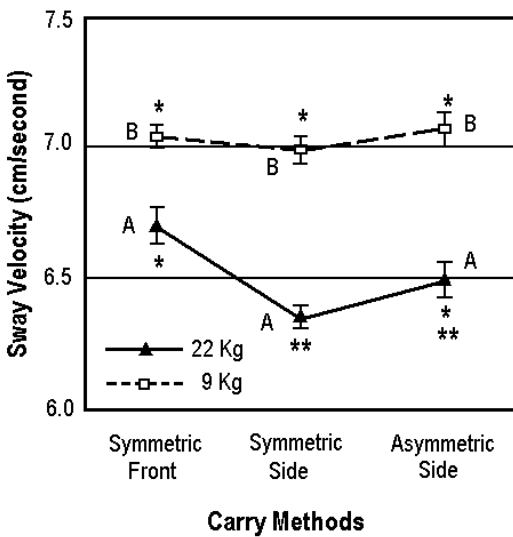
(a)

**End Frame Weight x Carry Method Interaction Effect on RMS AP Sway at Prestepping Stage**



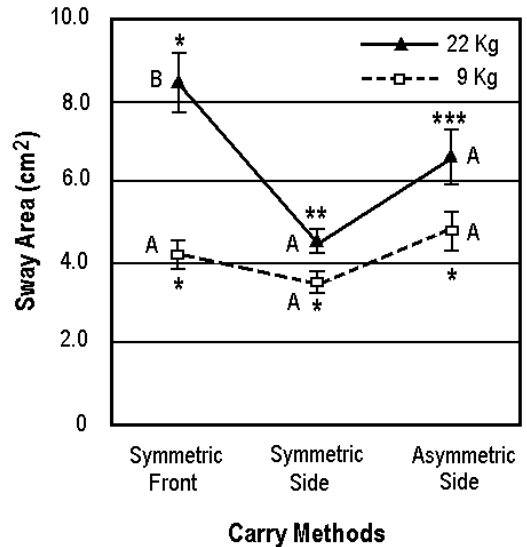
(b)

**End Frame Weight x Carry Method Interaction Effect on Sway Velocity at Prestepping Stage**



(c)

**End Frame Weight x Carry Method Interaction Effect on Sway Area at Prestepping Stage**



(d)

*Figure 3.* End frame weight by carrying method interaction effects on postural stability measured at the pre-stepping phase in (a) RMS of CP in the medial-lateral (ML) direction, (b) RMS of CP in the anterior-posterior (AP) direction, (c) sway velocity, and (d) sway area. Vertical bars in each graph represent standard errors. Within each carry method in each graph, same letter (A or B) indicates no statistical significance between the two weight groups. Within each weight level, different asterisks (\*, \*\*, and \*\*\*) indicate a significant difference between the carry method groups (at least  $p < .05$ ). It is worth noting that carrying a 9-kg frame resulted in statistically greater sway velocity than carrying a 22-kg frame at different rates for different carry methods (c); the practical differences (in the range of 0.3–0.6 cm/s), however, are insignificant. (RMS = root mean square; CP = center of pressure.)

area as compared with a 9-kg end-frame (7.720 vs. 4.925 cm<sup>2</sup>,  $p < .05$ ). Stepping on solid ground resulted in the smallest sway area, and this was significantly different from the sway area associated with the 7.5-cm and 10-cm thick urethane pad surfaces (3.4 vs. 7.75 and 8.56 cm<sup>2</sup>, respectively,  $p < .05$ ). Stepping in the forward direction resulted in the smallest sway area (4.18 cm<sup>2</sup>), followed by stepping in the lateral (6.35 cm<sup>2</sup>) and backward (8.45 cm<sup>2</sup>) directions ( $p < .05$ ).

### Task Difficulty

Analysis of task difficulty showed a significant effect of carrying method,  $F(2, 34) = 56.59$ ,  $p < .001$ , on the difficulty rating score and a significant increase in perceived task difficulty from the pre-step to the poststep phase for carrying the 22-kg frame. The symmetric front-carrying method (mean score of 4.21 for poststep action) was the most difficult among all three methods and had the greatest increase in task difficulty score: odds ratio (95% confidence interval [CI]) = 5.3 (1.9–14.6) as compared with the asymmetric side-carrying method.

There was no significant difference in mean score ratings between the symmetric and asymmetric side-carrying methods (1.78 vs. 2.01,  $p > .05$ ). The symmetric side-carrying method showed a lower increase in task difficulty: odds ratio (95% CI) = 0.5 (0.3–0.9) as compared with the asymmetric side-carrying method. Carrying a 9-kg scaffold frame is much less difficult than carrying a 22-kg frame; participants gave a difficulty rating of 1 for carrying a 9-kg scaffold frame.

### Summary of Results

The symmetric front-carrying method for handling the current 22-kg scaffold end frames was the least desirable approach based on the postural stability and difficulty ratings. The symmetric side-carrying method was the best option of the three methods, based on its low difficulty score and because it imposed the least postural instability before and after a stepping action, although the method did not offer any advantage in terms of stepping response time. Response time, postural instability, and task difficulty rating were significantly reduced when a 9-kg simulated end frame was used, as compared with a 22-kg end frame; differences in postural sway measurements among different carrying methods became insignificant when a 9-kg end frame was used.

Stepping to the side required the least response time, and stepping forward resulted in the least postural instability. A solid surface provided more security for stepping actions than did urethane-padded surfaces; the increased postural instability was correlated to the surface deflection level.

## DISCUSSION

### Carrying Method

Statistical tests showed that no single carrying method seemed to have an advantage over the others on response time. Detail examinations of the three scaffold-carrying postures showed that all three methods placed the center of mass of the scaffold end frame very close to the body of the participants (although at different heights), and thus the time required to overcome the inertia for each method was nearly the same. The contribution of end frame weight, direction of movement, and surface type effects on response time overwhelmed the effect of carrying method.

The symmetric front-carrying method was the most difficult way to handle the current 22-kg end frame and yielded the greatest instability in all postural sway measurements. This result is in line with reports that a load results in increased instability when the center of gravity of the load is raised (Holbein & Redfern, 1997), especially above the waist (Davis, 1983).

### Scaffold Weight

This study showed that performing a stepping movement while carrying a 9-kg end frame required 5.9% to 9.7% less stepping time, as compared with carrying a 22-kg load. This is understandable in that transferring a lighter load requires a worker to overcome a smaller inertia at the beginning of the task, thereby requiring a response time shorter than that associated with handling a heavy load. This study also showed that reduced scaffold weight decreased postural instability.

In this regard, reducing the current scaffold end frame weight from 22 kg to the 9-kg level (e.g., by using reinforced, lightweight composite materials) would be a viable engineering control to reduce the risk of scaffold handlers being struck by an object, falling, or suffering overexertion injuries during scaffold erection and dismantling. This is a worthwhile consideration for design of next-generation scaffolds. In fact, composite-material scaffolds are commercially available in some forms

now. Further studies can be performed to identify the optimal end frame weight (e.g., between 9 and 22 kg) that meets scaffold structural strength requirements and provides an acceptable worker instability risk and task difficulty level.

### Work Surface

The finding that nonrigid surfaces significantly increased workers' stepping response time and postural instability is consistent with the results of Marigold and Patla (2005), who reported that an increase in the compliance level of a nonrigid surface resulted in increased recovery/response time and compromised trunk stability. For scaffold workers, these results imply that as their working area changes from a firm surface to a nonrigid surface (e.g., a wood plank), the environment becomes more unstable and the worker becomes more unbalanced, losing the ability to respond quickly in a hazardous situation.

A future study on the human postural instability threshold and further analyses of the postural sway data collected in this study would establish a dose-response relation between surface firmness and postural stability. It may help to identify a natural or critical cutoff firmness level for workers to select adequate planks and to discard certain overly used planks.

### Direction of Movement

The literature has shown that for healthy individuals with no load-carrying conditions, stepping backward takes more time than stepping forward, and stepping forward requires more time than stepping aside (Patla et al., 1993). This study demonstrated the similar effect of direction of movement on stepping response time during lightweight (9 kg) and medium-weight (22 kg) carrying conditions.

### Limitations and Future Directions

Previous studies have reported that body weight transfer time (stepping response time with no load carrying) increases with age (Patla et al., 1993) and that the effects of carrying a load on walking patterns are different between men and women (Martin & Nelson, 1986). Future studies can be designed to include older and female participants, in that older workers and women are increasingly found in occupations in which scaffolding is used.

This study used urethane pads topped with a plywood plate to simulate three nonrigid surfaces. With the recent development of virtual reality tech-

nologies for scaffolding safety research (Hsiao et al., 2005), the study can be further extended to evaluate the strategies for carrying scaffold end frames on real scaffold planks within simulated virtual heights. Such an experimental setup could minimize the differences between the simulated planks in this study and the real planks in the construction field.

In a study on human responses to an augmented virtual scaffolding environment, Hsiao et al. (2005) found that scaffold heights affected human walking patterns, as measured by stride length. Construction and nonconstruction workers showed significant differences in stride width and stride instability scores. The study also indicated a significant learning effect in stride length. In a study dealing with responses to unexpected surface softness, Marigold and Patla (2005) also noted a learning or expectation effect.

In our study, construction workers with a minimum of 6 months' scaffolding job experience were tested near the ground under various nonrigid surface conditions for one stepping trial each. The study can be expanded to include worker experience, scaffold height, worksite environment parameters (e.g., lighting level and slipperiness), and multiple trials. The practical implications of these extensions would be in the development of programs for balance control training to reduce the risk of falls at elevations before workers enter a scaffold-handling job.

## CONCLUSION

Based on the results of this study, the symmetric side-carrying method is the best option of the three common methods for handling the current 22-kg scaffold end frames. A solid surface provided more security stepping actions than a soft surface; increased postural instability was correlated to the surface deflection level. Response time, postural instability, and task difficulty were reduced when a 9-kg simulated end frame was used. Considering all these factors, scaffold erectors may want to adopt the symmetric side-carrying method as the primary technique and to maintain their scaffold planks at firm conditions as much as possible. Developing a new generation of lightweight scaffold end frames offers a potential to reduce the risk of scaffold handlers being struck by an object, falling, or suffering overexertion injuries.

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